

RF SYSTEM HARDWARE IMPROVEMENTS AND NEW PROCEDURES

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Abstract

A substantial program of RF system hardware improvements was undertaken in the 1998/99 shut-down and continued during the 1999 running period. This included waveguide system adjustments to reduce field spread, installation of damping systems to avoid ponderomotive instabilities and the installation of vector sum feedback in a number of units to improve stability. While some of this work is still ongoing important performance improvements have been gained. Procedures introduced during 1999 such as automatic RF unit switch on and automatic frequency shift have become invaluable in operation. Running at higher beam energies in 1999 has however brought some increased operational difficulties. These will be discussed and some solutions which can be implemented for 2000 running are presented.

1 INTRODUCTION

As well as the addition of cavities, a large number of other hardware modifications and improvements have been undertaken on the RF system to obtain the best possible performance for high energy high intensity running. While some of these have been completed, such as extensive waveguide system measurements and adjustments, others such as the installation and commissioning of active damping and vector sum feedback are still ongoing. The general program of reliability improvements and creation of software facilities to improve operation also continues. Although the performance of the RF system was generally excellent in 1999, running at much increased gradients and RF powers has revealed some weak points. For example, improvements on certain water loads in the waveguide system are needed. Operation at high energy, towards the end of the 1999 running period was more difficult than expected and intensity had to be substantially reduced to allow running. The cause of this limitation is not fully understood and some improved diagnostic facilities are needed for the 2000 running period. Ultimately, at the highest possible energies, it becomes important to ensure that nearly all the time when the RF is at full voltage is used for physics, i.e. spending as little as possible of that time in preparation for physics. The 'Mini-Ramp' strategy for the end of the acceleration process, successfully tried out in 1999 to accelerate to 102 GeV, achieves this. It is probably the only way to achieve luminosity at the energy corresponding to the out and out RF limit with no reserve.

2 FIELD SPREAD DURING ACCUMULATION AND AT TOP ENERGY

In 1998 problems were caused by large field differences between individual cavities during filling and at high energy in certain half-units. This was particularly critical with high current at injection, since the combined effects of high beam loading and ϕ_s being near 180 degrees result in very large cavity detuning.

The main causes identified were:

- Waveguide length differences.
- Cavity coupler Qexternal differences.
- Imperfections in waveguide hybrids and loads.
- Imperfectly matched loads, resulting in reflections.
- Tuning system errors.

Waveguide system measurements and adjustments, described last year [1], were successfully completed during the 1998/99 shutdown.

The main modifications carried out were:

- Adjustments to waveguide lengths in 12 half-units.
- Insertion of $\lambda/4$ waveguide transformers in input waveguides for 41 cavities.
- Changing of loads on all tuning reference directional couplers.

The effects at injection are shown in figures A1-1 to A1-4. For each RF point the field distribution in all cavities taken during a high intensity injection MD in 1998 (8.3 mA injected with 8 bunches on 8) is compared with a typical fill in 1999 (6.0 mA with 4 on 4). The results show that an overall improvement has been obtained and that for several cavities having very high fields in 1998, particularly in points 2 and 8, fields have been brought to normal levels. This now prevents other cavities being forced to very low fields and detuning. Similar comparisons, but at top energy, between 1998 running (6.0 mA at 94.5 GeV) and 1999 running (5.5 mA at 100 GeV) are shown in figures A2-1 to A2-4. Note that the fields in the 1999 case are much higher than in the 1998 case. While improvements have been gained, the results obtained are not as good as had been expected. However the detuning of cavities during accumulation was not a problem for operation in 1999. Any tendency for fields to decrease dramatically could be cured by small cavity tuning setpoint trims automatically loaded at injection, contrary to the situation in 1998. The effect of taking out a small injection setpoint offset of 3 degrees in one cavity (C13) in Unit 633 is shown in figure 1. Equalising fields at high energy is far more difficult. Larger setpoint changes are required since the cavities are already closer to tune and the required adjustment can too easily provoke instabilities due to ponderomotive effects or circulator oscillations (see later). The possibility of

adding 1/4 waveguide transformers remains a possibility to improve large differences, however there were no cases sufficiently serious to justify intervention in the 1999/2000 shutdown.

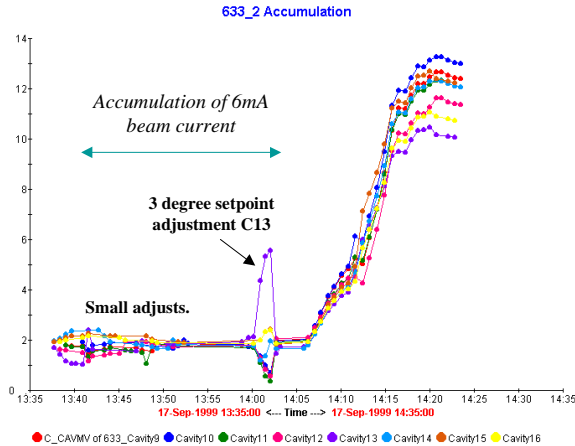


Figure 1: Effect of single cavity setpoint adjustment on field distribution at injection.

3 WAVEGUIDE SYSTEM MODIFICATIONS FOR 2000

Waveguide system modifications concern the 100 kW water loads on the first magic tee and the 300 kW loads on the circulator in the SC units. For the 100 kW load imbalance from detuned cavities can produce up to 300 kW and very high temperatures in these loads. The weak point is the polystyrene coaxial insulator at the input end. Loads in 31 SC half-units will be fitted with teflon insulators and for the remaining five 300 kW loads recuperated from removed copper units will be used. In selected half-units the 300 kW circulator loads will be replaced by a longer 6 m version with increased water

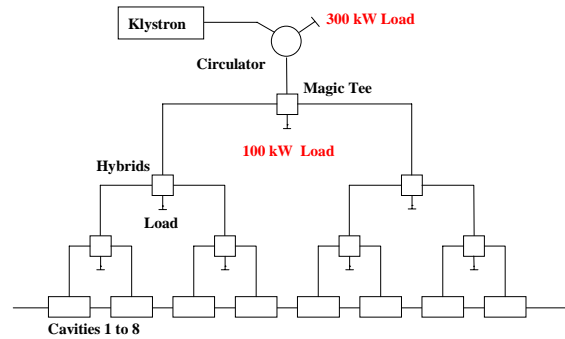


Figure 2: SC half-unit showing critical water loads

flow to give improved temperature stability. This will allow better control of low-frequency oscillations due to circulator reflected power. (See later)

4 PONDEROMOTIVE OSCILLATIONS AND ACTIVE DAMPING

The standard tuning control loop is de-stabilized by cavity mechanical resonances and ponderomotive effects. The forward loop is therefore constrained have to a low cut-off frequency and consequently provides no damping of resonances or of ponderomotive oscillations. A narrow band compensation system has been developed (Active Damping) which introduces a band limited component of the tuning phase error signal, with carefully adjusted phase and amplitude, near the mechanical resonance frequency. Successful damping with this system was demonstrated towards the end of 1998. A variation using amplitude instead of phase was also tried out but so far has not produced such good results. Active damping hardware was constructed and installed in the RF controls racks for all 288 cavities during 1999. Setting up is done individually for each cavity. Usually a half-unit, with 8

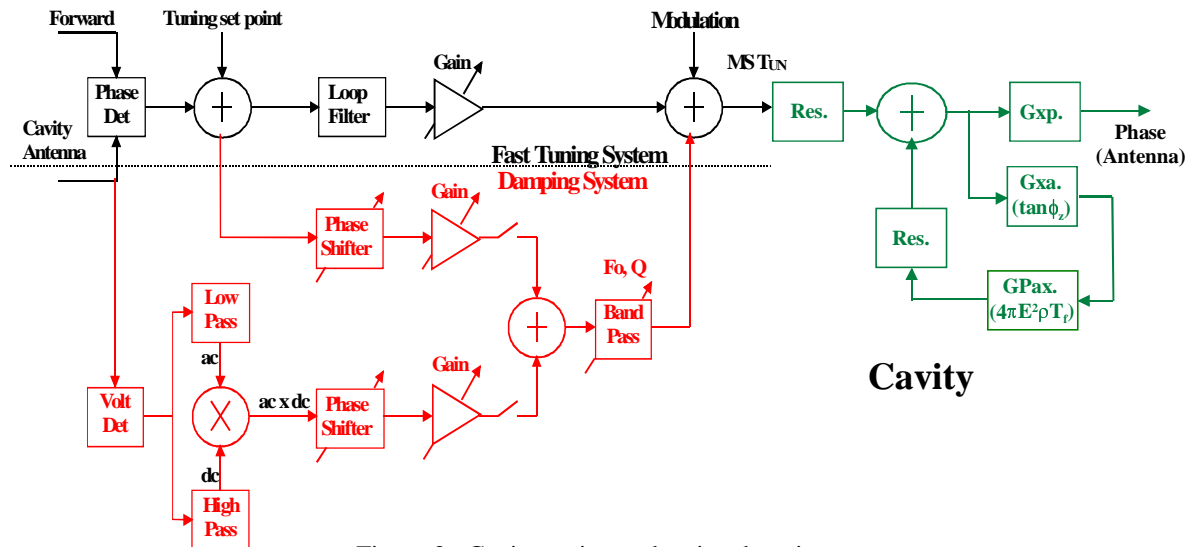


Figure 3: Cavity tuning and active damping.

cavities, is done during RF maintenance or some other convenient time, taking typically 2 hours. Active damping is now operational for all cavities in Point 8 cavities and for roughly half in Point 2. In general the results obtained have been very good and most of the cavities now set up show no sign of oscillations during normal operation. There are however some cases in which the oscillations do remain, in spite of the set up procedure being successfully carried out. This is explained in some cases by the presence of two resonances close to each other in frequency with similar amplitudes. Additionally for some cavities residual cryogenic oscillations make setting up difficult and the damping is less effective.

The effect of active damping is shown in figures 4 and 5. Figure 4 shows the evolution of the peak to peak values of the cavity fields, i.e. the oscillation amplitudes, for cavities 13 to 16 in unit 872_2 just after setting up of active damping.

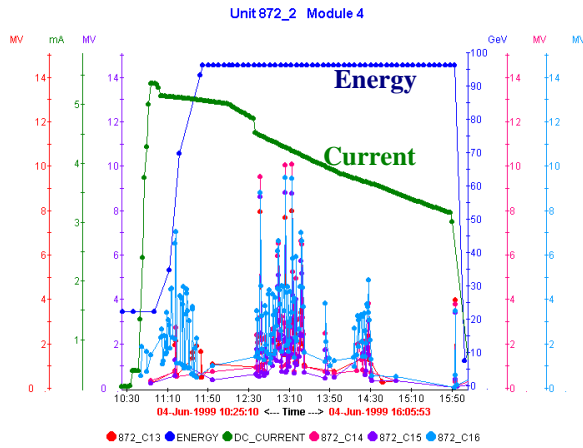


Figure 4: Field oscillations in 872 M4 with no active damping

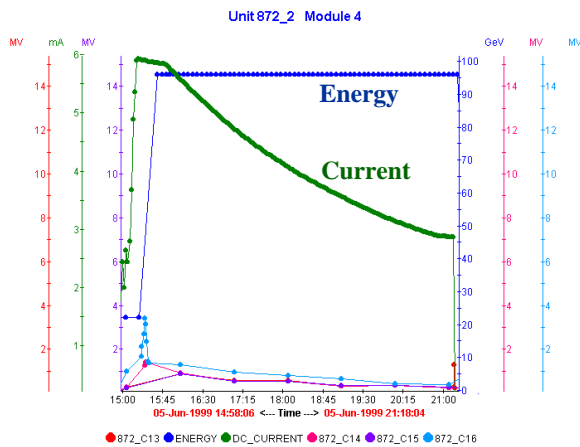


Figure 5: Field oscillations in 872 M4 with active damping.

Large oscillations occur during the ramp since the cavity detuning is large and conditions for ponderomotive oscillations are enhanced. A subsequent fill with the active damping switched on is shown in figure 5. Here oscillations are completely damped, even with higher beam current than in the previous case.

‘Supelec’ Active Damping

This results from a study of the tuning system and cavity undertaken by D. Boussard and D. Beauvois of Supelec in Paris. Using the theoretical model together with actual loop responses measured on a set of 10 cavities the aim was to find the best compensating network giving the following features:

- a) Maximum damping and robustness i.e. good stability margins under all operating conditions.
- b) The same network should be useable on all cavities to avoid long and complicated setting up.

Using Matlab and Simulink a fourth order corrector having the following characteristic was developed:

$$\frac{Y(S)}{U(S)} = \frac{-93.77S^3 - 3.192e5S^2 - 3.839e7S - 1.187e11}{S^4 + 55.24S^3 + 8.812e5S^2 + 2.594e7S + 1.853e11}$$

The frequency response is shown in figure 6.

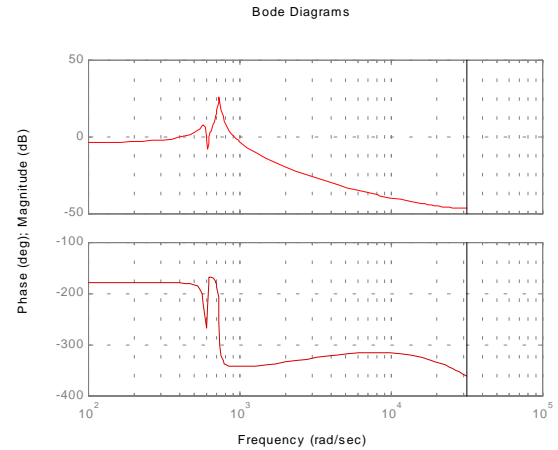


Figure 6: Frequency characteristic of Supelec corrector.

The response shows peaks near, but not exactly on, the two most important cavity mechanical resonances. This corrector was implemented on a Analog Devices SHARC DSP (32 bit FP 40 MHz Clock) as an IIR filter with a sampling frequency of 10 kHz. The measured response, shown in figure 7, corresponds exactly to the theoretical characteristic.

The corrector was tested in half unit 471_2 which contains 8 cavities of the set provided for the corrector design. Successful damping was produced for cavities 5 to 8 (CERCA 2018). Cavities 5 to 7 needed no

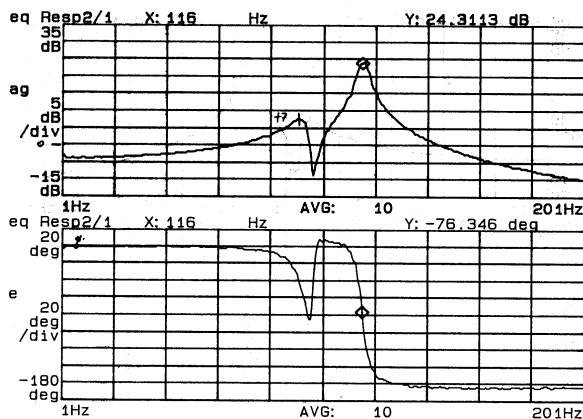


Figure 7: Measured frequency response of DSP implementation

adjustment but cavity 8 needed the gain to be reduced to one half. For the other four cavities, Cavities 1 to 4 (CERCA 2013) the damping had no effect. The successful damping of cavities 5 to 8 is shown in figure 8, which shows the oscillation amplitudes during ramping.

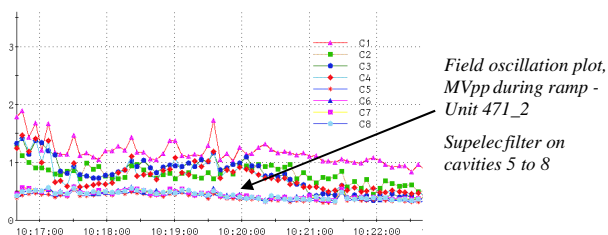


Figure 8: Effect of Supelec damping in 471_2

Further tests are planned for the coming running period to determine what modifications might need to be made to the corrector. The main interest in this system is that it might be able to produce damping for cavities for which the normal damping system has not been able to give good results.

5 VECTOR SUM FEEDBACK

Vector sum was used with increased success in 1999 and was installed in 5 half-units at Point 8 (873_1, 871_1, 831_2, 872_2 and 872_2). Repair of a systematic fault found in the klystron drive amplifiers may have contributed to the improved reliability. The important advantages of Vector Sum feedback are:

- Improved stability, together with cavity active damping.
- Elimination of low frequency oscillations due to reflected power from circulator

- Power is quickly available to compensate the change in beam loading conditions if other units trips.
- The effects of beam loss are rapidly compensated and tripping of the RF unit on beam loss is avoided.

There are some difficulties however:

- Setting up is long and complex, many cables have to be installed and measured.
- Dynamic range limitations are imposed by the klystrons. If the drive is low, for example at injection, there will be high collector dissipation which leads to vacuum problems and in the long term reduces the lifetime of the klystron. On the other hand at top energy, with high drive power, certain klystrons are prone to sidebands. These sidebands have adverse effects on the beam.
- In general diagnostics are more difficult because of the fast feedback loop.

As in previous years, installation, set up and testing times are very limited in 2000. However it is planned to install vector sum feedback in several units, including some at point 6 which are particularly prone to low frequency oscillations originating from the circulator.

Low frequency oscillations

These can occur in the RF unit if reflected power is returned to the cavities. This causes detuning of the cavities via the tuning system which finds incorrect forward reference, causing further reflected power to the circulator. This builds up into an oscillatory situation. The spectrum of a typical case is shown in figure 9.

It is important to distinguish between these oscillations and cavity ponderomotive oscillations when adjusting

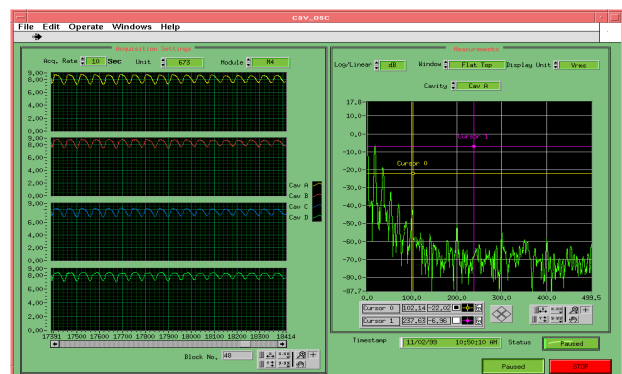


Figure 9: LF oscillations and spectra. Unit 673 C13-15

cavity tuning setpoints since both effects are sensitive to setpoints. The cure is good adjustment of the circulator, which is facilitated by a stable circulator load as mentioned earlier. Vector sum feedback also effectively damps these oscillations. These oscillations are particularly dangerous for the beam, the frequencies are well inside the cavity bandwidth and they are transmitted via the beam to other RF units.

6 FEEDBACK SYSTEMS

Transverse Feedback

Transverse feedback was little used in 1999 but remains operational for 2000.

Longitudinal Feedback

Longitudinal feedback was used systematically until problems occurred on a vacuum transition. Lack of vacuum gauges following the incident prevented conditioning. Several cables in the tunnel are degraded and some are impossible to change due to restricted access around the equipment. However it is planned to make this system as operational as possible then do conditioning and testing for the start-up.

2 Qs Feedback

This system was installed in 1999 and used for electrons only. It provides damping of the signals but with the feedback on accumulation is less efficient. The reason is not understood.

7 HARDWARE AND RELIABILITY IMPROVEMENTS

The main modifications done during 1999 were the klystron drive amplifier modifications already mentioned, the re-calibration of RF voltage to allow the maximum to be increased from 100 to 125 MV and the increase of maximum cavity field limit from 9.6 to 10.8 MV/m to limit spurious trips.

For 2000 all 288 MS tuner drive power supplies will be fitted with higher voltage and current rated rectifier diodes to improve reliability. Current sources for SC cavity temperature measurements were another weak point in 1999 and a batch with a number of improvements is in preparation for running in 2000. Similarly for HOM coupler temperature measurements a new module with better noise immunity and more flexible operating modes has been developed.

8 SOFTWARE AND PROCEDURES

In 1999 RF unit automatic switch on was made operational and used throughout the year in physics. Automatic procedures were used to take out the positive frequency trim normally introduced in physics when the available RF voltage margin became too small and to re-introduce it when the voltage margin became sufficient. Cavity setpoints were still used to minimise ponderomotive oscillations, manual or automatic adjustment methods being used. Five nominal settings were resident in the cavity equipment as shown in table 1.

| | Nominal Setpoint | Use |
|---|--------------------------|-------------------------------|
| 1 | Resonance | Reference value |
| 2 | Injection | Field adjustment at injection |
| 3 | High energy high current | End of ramp/start of coast |
| 4 | High energy low current | End of coast |
| 5 | High energy no current | RF tests with no beam |

Table 1: Cavity nominal setpoints

Even with active damping installed in many cavities the possibility to switch between various nominal values was retained and caused no inconvenience. During the coast the setpoints were backed off automatically using linear interpolation with beam current to obtain best overall stability. The RF system ORACLE based data logging system was completed in 1999 and was extremely useful for fault diagnostics and statistics. Automatic RF unit phasing based on power and field measurements was not done.

Operational problems at the end of 1999

Further improvements planned for 2000 are the outcome of experience during the relatively difficult running period at 101 GeV the end of 1999. Many fills were lost on or just after start of physics, for unclear reasons. Hardware problems such as broken water loads and intermittent phase jumps were certainly present but the effects not always easy to detect. The cryogenic system at Point 4 may have been near its limit. Since many beams were lost very shortly after going into collision the effects of beam scattered from the IPs reaching the cavities was also suspected, but this could not be verified.

A major difficulty was to determine which of the tripped units had caused the beam loss. With the high power operating conditions the beam loss itself would cause the trip of many other RF units – all within a very short period. The behaviour of the RF unit on the loss of the beam is shown in figure 10.

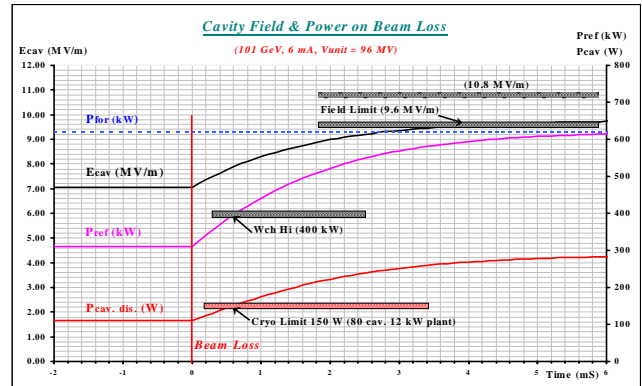


Figure 10: Effect of beam loss in RF unit

This shows the situation corresponding to 101 GeV with 6 mA beam current for an RF unit providing 96 MV. The forward power is 620 kW. When the beam is lost the beam induced component of the cavity voltage, which opposes the applied (generator) voltage, decays exponentially with a time constant equal to that if the cavity filling time (around 2 mS). In the absence of fast feedback (i.e. no Vector Sum) the cavity field will rise towards a value exceeding 9.2 MV/m with practically all forward power reflected. Under these conditions one of the following will provoke a trip:

- Field Limit interlock – Set to 10.8 MV
- Reflected Power interlock – The limit is set for protection of the circulator at 400 kW.
- Field emission - activation of surface emitters in the cavity provoking rapid helium pressure rise.

Note that the moving of the field limit interlock level from 9.6 to 10.8 MV/m substantially decreased the number of trips due to this interlock on beam loss, as would be expected from Figure 10. The total number of trips remained unchanged however since the other effects and protections act instead.

The above effects are very rapid, occurring a few milliseconds after the beam loss. Similarly RF unit trips can provoke rapid beam loss.

RF unit trip and beam loss sequence diagnostics

Local RF unit hardware and software diagnoses the cause of a trip, which is time-stamped with a resolution of one second. The real precision of this is heavily dependent on the accuracy and setting of local clocks in individual equipment controllers in the various RF units. It is therefore not sufficiently accurate to provide the true overall RF unit trip sequence. A fast synchronised diagnostic system is needed. The system has to provide the sequence of RF unit trips causing beam loss, information on the beam loss itself and the resulting sequence of unit trips.

A system based on GPS timing is being developed. This is very attractive since already installed GPS receivers in each point of LEP can be used. GPS permits events to be time-stamped to a precision of 10 uS. The system is shown in figure 11 and is based on the use of one GPS IRIG-B repeater in each RF sector, installed in one RF unit 'Data Manager' VME controller. Relevant status information such as the RF switch states for each half-unit and HV Main Circuit Breaker states are brought to a fast microprocessor (a DSP will be used). This timestamps any changes in state locally and triggers the GPS module, obtaining an accurate timestamp via a serial communication with the DM which it uses to re-synchronise its own clock if necessary. In this way an event table containing state changes with timestamps can

be built up in the microprocessor. This is shown in figure 12.

DSP Event Table - RF Sector:

| Event | Counters | | STATES | | | | | | | | GPS Timestamp HH:MM:SS.mmm,uuu |
|-------|----------|------|--------|-----|-----|-----|-----|-----|-----|---|-----------------------------------|
| | Secs | usec | MB1 | RF1 | MB2 | RF2 | MB3 | RF3 | RF3 | | |
| 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 08:52:01.234.456 |
| 1 | 1800 | 700 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 09:22:01.235.156 |
| 2 | 1920 | 3200 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 09:24:01.237.656 |
| 3 | 1920 | 3250 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | - |
| 4 | 1980 | 1120 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 09:25:01.235.656 |
| 5 | 1980 | 3020 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 09:25:01.237.476 |
| 6 | | | | | | | | | | | |

Beam Loss :

| Event | Counters | | STATES/LEVELS | | GPS Timestamp HH:MM:SS.mmm,uuu |
|-------|----------|--------|---------------|--------------------|-----------------------------------|
| | Secs | usec | Beam Det | Beam Current mA | |
| 0 | 0 | 0 | 1 | 8.2 | 08:52:01.250.870 |
| 1 | 288 | 880 | 1 | 8.1 | 08:56:49.251.750 |
| 2 | 514 | 345690 | 1 | 8.0 | 09:00:35.596.560 |
| 3 | 1023 | 88020 | 1 | 7.7 | 09:24:01.237.656 |
| 4 | 1979 | 984790 | 1 | 3.2 | 09:25:01.235.600 |
| 5 | 1979 | 984790 | 0 | 0.0 | 09:25:01.235.660 |

One system at
Point 6

Figure 12: Event tables for RF unit state and beam intensity threshold changes

A similar system installed at just one place in the machine could monitor beam intensity on a turn by turn basis, logging beam current changes. These tables would be loaded to the DM on request and an overall application program would use the data to re-constitute the complete RF unit trip history in all four RF points and compare with beam loss history.

Operational procedures for 2000

The GVC 'Survival Mode' introduced in 1998 but not really used in operation will be re-introduced into *Sloppysoft*. The database reference maximum RF unit voltage levels in 1999 were typically values which were determined at the end-of-fill after 'pushing-up' the RF voltage. These levels could not be sustained so easily at the beginning of a fill with higher beam current, increasing the tendency for multiple unit trips. In 'Survival Mode' the GVC sets a lower level with just sufficient quantum lifetime and keeping the voltages below maximum until tripped units are switched on again.

Since higher energies are expected in 2000 the 'RF Stop' towards the end of the ramp should be moved from 96 to 98 GeV to reduce the cavity detuning when the RF voltage is raised to minimise the effects of ponderomotive oscillations.

The 'Mini-Ramp' procedure tested in 1999 to ramp colliding beams from 101 to 102 GeV is the most promising strategy for obtaining luminosity at the highest attainable energy. Clearly if highest energy physics can start as quickly as possible after the RF voltage is put to maximum the integrated luminosity over a given period will be higher. Optimum operating scenarios are discussed in other presentations at this workshop. [3,4] It may also help to make diagnostics on the cause of beam losses easier as voltage increase and energy ramp can be done in smaller steps.

If both energy and intensity are pushed higher in 2000, with corresponding higher RF powers, a greater number of units would trip on beam loss for the reasons described earlier. The possibility of switching all RF units off as soon as beam is lost could be implemented if any risk of damage is suspected. This would be relatively easy using the existing cabling and hardware of the original RF beam dump system.

9 SUMMARY AND CONCLUSIONS

The main RF system hardware modifications and new procedures for running in the year 2000 have been outlined:

- Certain loads in the waveguide system will be changed for better power handling.
- Installation of cavity active damping systems will be completed and tests with Supelec and other systems continued.
- Vector sum will be installed in more RF units.
- New GPS based diagnostics systems for RF trip and beam loss history will be installed.
- Minor modifications will be made to the GVC.
- Some minor additional software items will be implemented.
- The end of ramp procedures will be changed for the ‘Mini-Ramp’ to provide best optimised running at the highest possible LEP energy.

10 ACKNOWLEDGEMENTS

Thanks are due to all members of the LRF group involved in the work described and for all the information they provided.

11 REFERENCES

- [1] E. Ciapala, “The RF System at Injection and Ramp”, Proceedings of the Workshop on LEP-SPS Performance Chamonix IX, 1999.
- [2] D. Beauvois, “Etude d’une cavité électromagnétique”, Supelec Report 1998.
- [3] M. Lamont, “Strategies for Maximising Energy and Luminosity”, this workshop.
- [4] P. Janot, “What are the Priorities for LEP in its Final Year?”, this workshop.

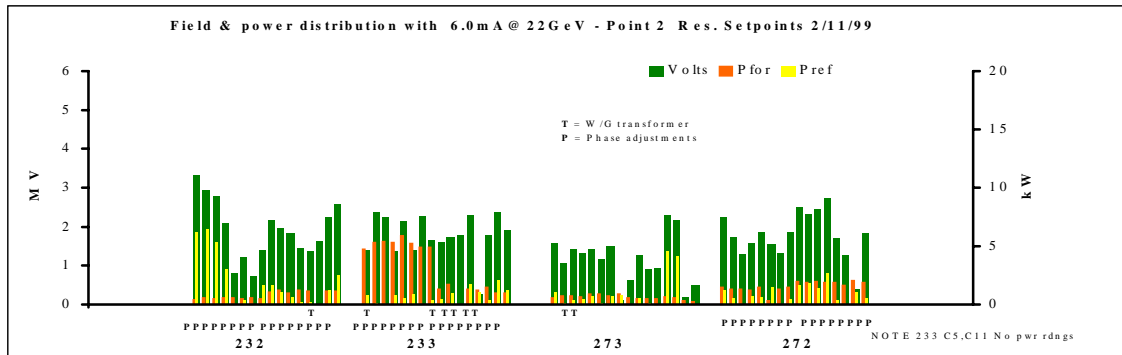
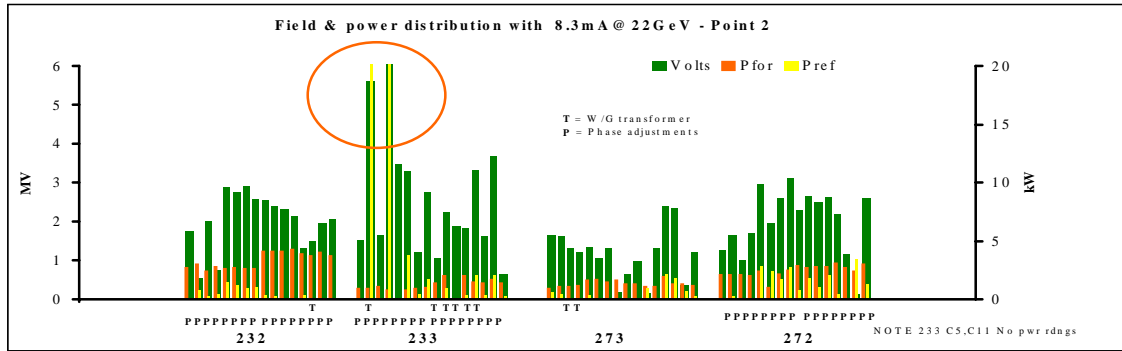


Figure A1-1 Field distributions at injection – Point 2

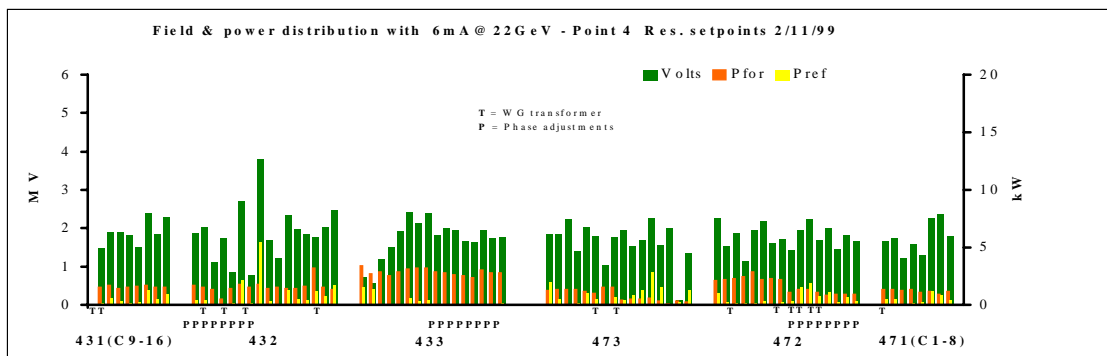
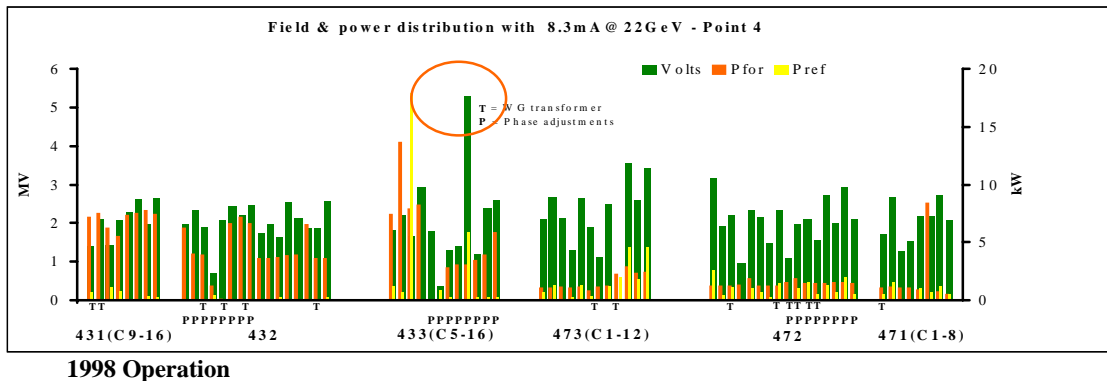
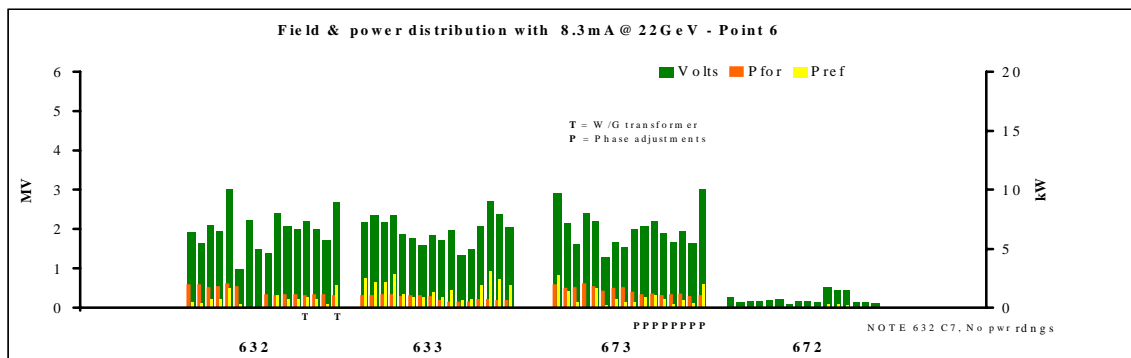
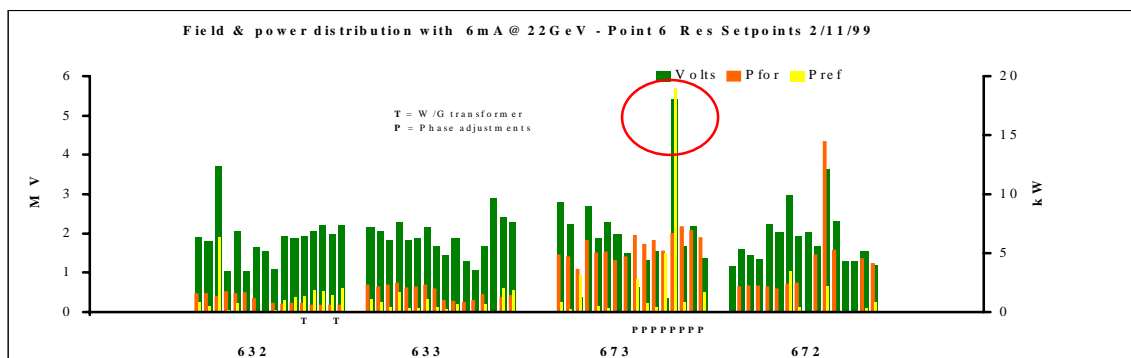


Figure A1-2 Field distributions at injection – Point 4

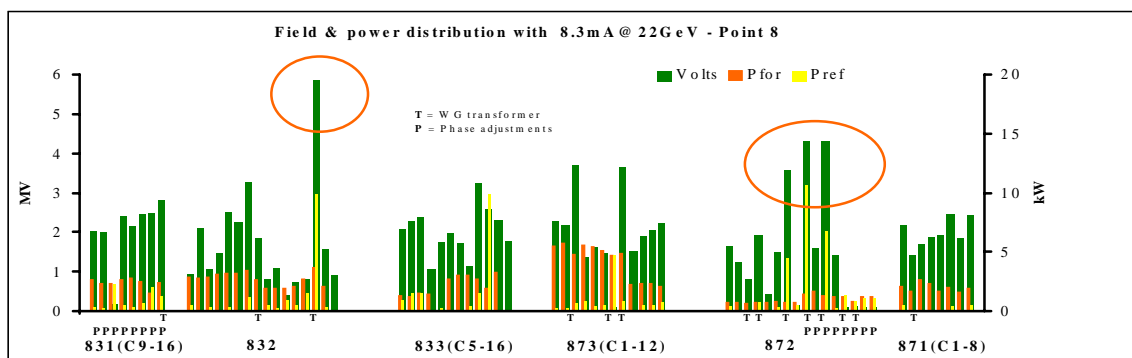


1998 Operation

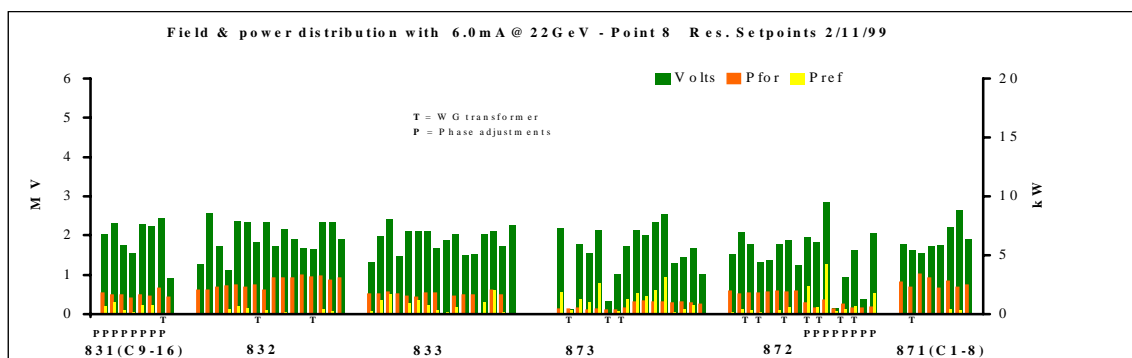


1999 Operation

Figure A1-3 Field distributions at injection – Point 6



1998 Operation



1999 Operation

Figure A1-4 Field distributions at injection – Point 8

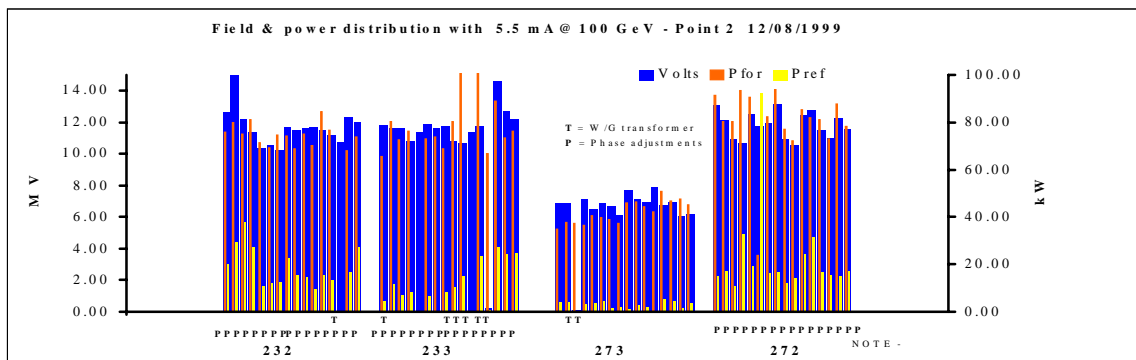
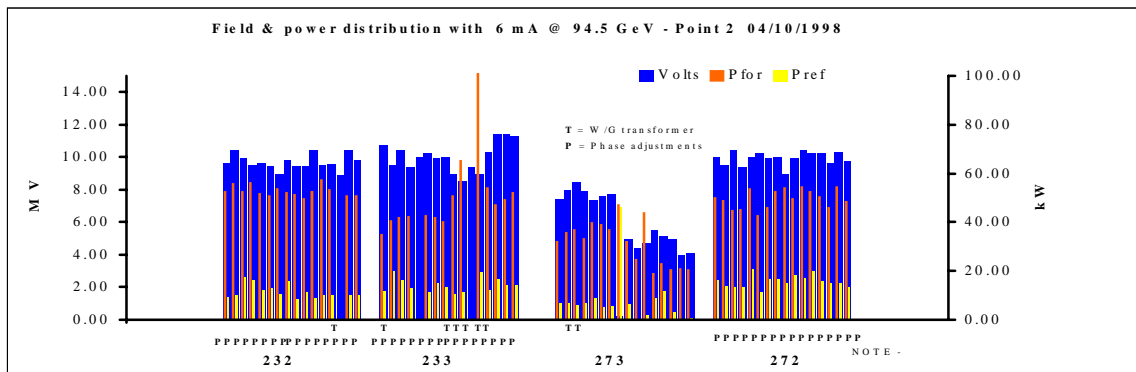


Figure A2-1 Field distributions at top energy – Point 2

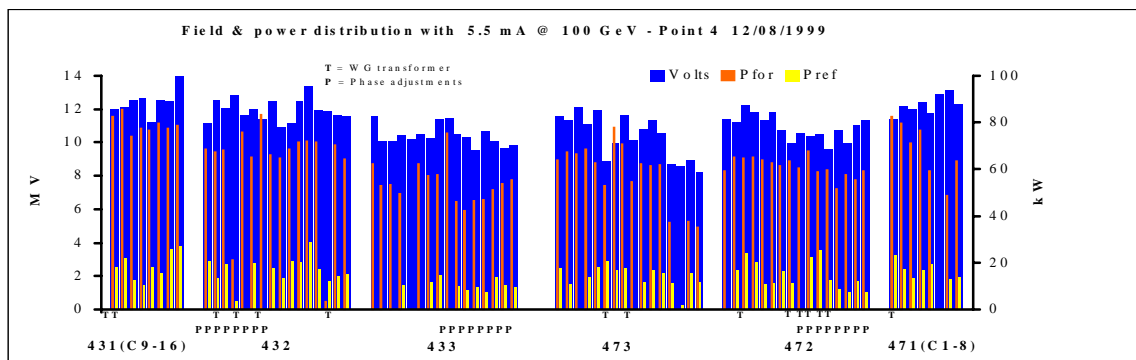
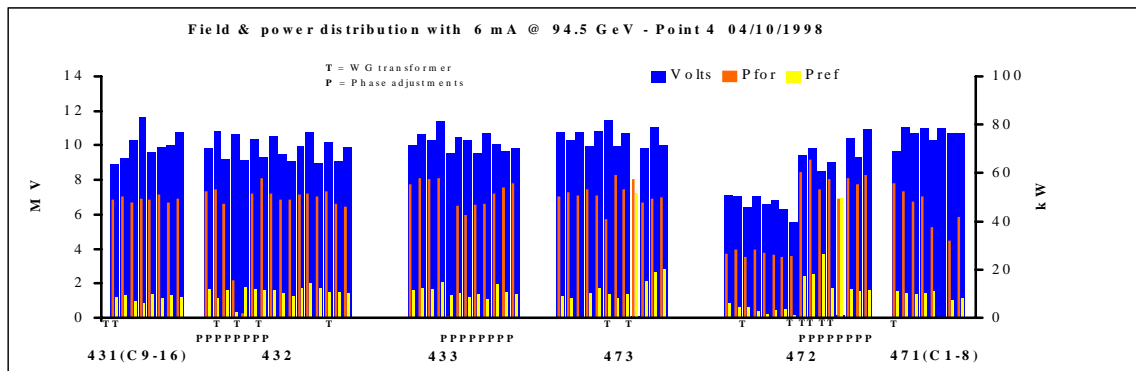
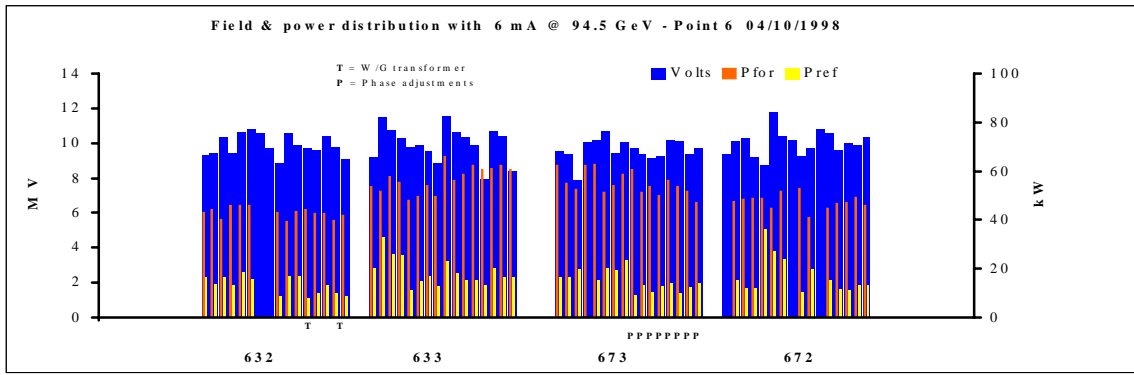
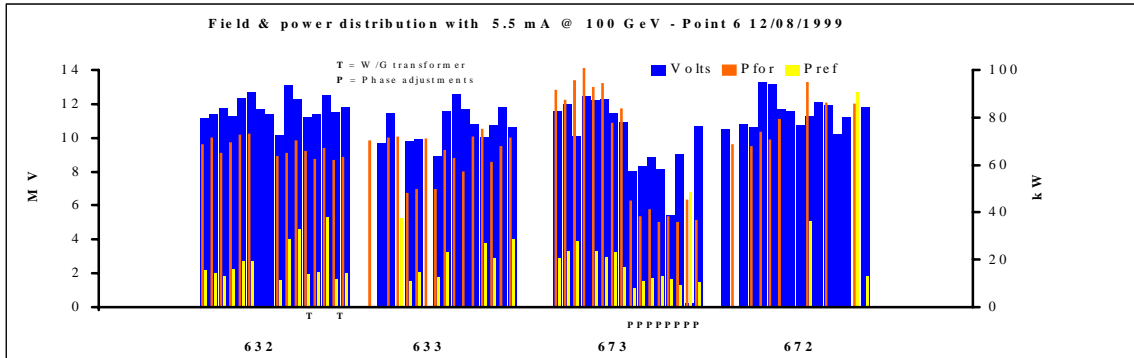


Figure A2-2 Field distributions at top energy – Point 4

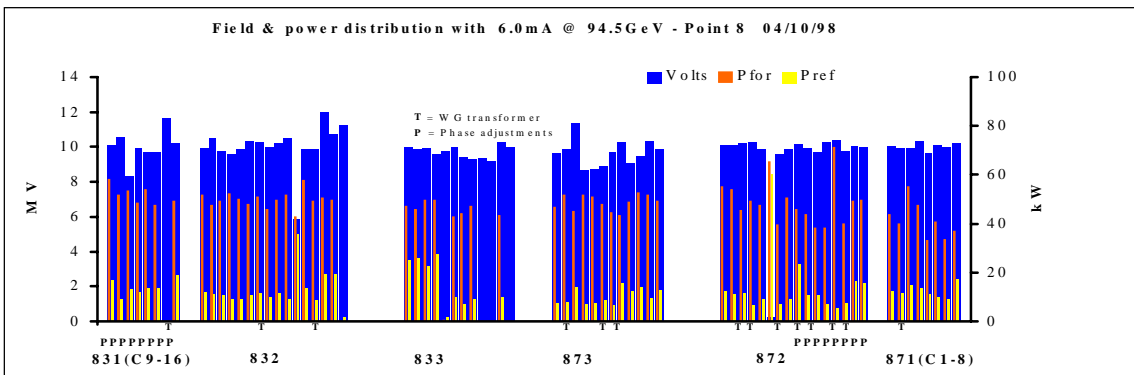


1998 Operation

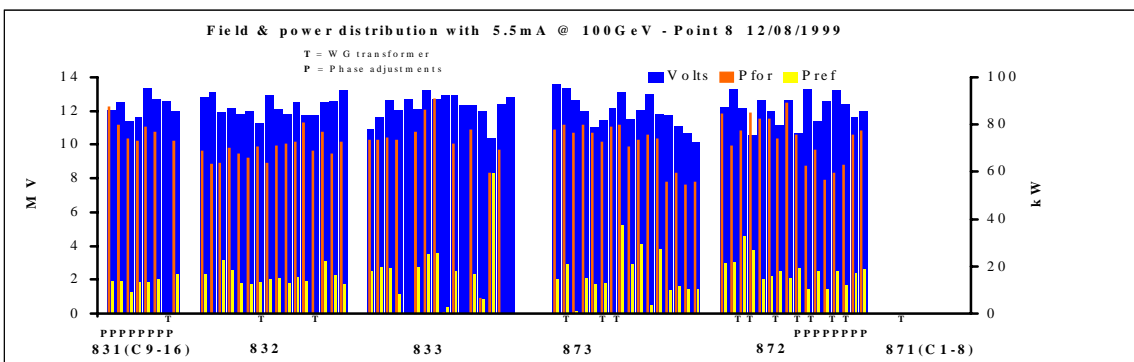


1999 Operation

Figure A2-3 Field distributions at top energy – Point 6



1998 Operation



1999 Operation

Figure A2-4 Field distributions at top energy – Point 8